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HOLOGRAPHIC DIFFRACTION GRATINGS

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The study of the physical and chemical properties of elements is more and more requiring the use of spectral analysis apparatus. Of the spectrometers designed for this purpose, the oldest is the prism spectrometer, gradually being replaced by grating spectrometers and Michelson and Fabry-Perrot interferometers with higher resolving power and greater brightness. The latter two instruments, however, handle delicately and their results are too accurate and detailed to be easily analyzed. A computer must be combined with the Michelson interferometer and, for very accurate studies on the hyperfine structure of rays or isotopic effects, the luminous flux is usually filtered with a diffraction grating monochromator (with fairly low resolving power) before analysis with a Fabry-Perrot interferometer. The gratings, whether inside the spectrometers (for spectral analysis) or inside monochromators (for isolating radiation) are by far the easiest to handle of the dispersing instruments.

Two essential qualities are demanded of gratings, as of any optical instrument: good image quality, and luminosity.

Defects of Classical Gratings

Classical gratings are engraved with a diamond on a plane or concave aluminum-plated substrate. The ruling speed is about 600 lines per hour; gratings are currently made with 1200 rulings per millimeter so that two hours are needed to rule 1 mm and nearly

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*Numbers in right hand margin indicate pagination of foreign text.

two weeks to make a grating on a stand 150 mm long. The quality of the images diffracted by a grating depends on the planeness of the substrate, the straightness of the grooves, and proper attention to the distance between two neighboring grooves ("pitch"). These mechanically-engraved gratings possess defects, the consequences /764 of which justify a search for other manufacturing methods. If the screw holding down the stand slips after one groove has been ruled, periodic defects will result in "ghosts" in the spectra. Moreover, random errors in placement of the rulings introduce a source of diffuse light. Also, a grating is never used on its own: it is always mounted in a spectrometer, which in general, includes two spherical mirrors. These mirrors introduce aberrations. One might think of using the dispersion and focusing properties of concave gratings, but they, too, have aberrations (in particular, astigmatism and coma).

We can now reduce the number of ghosts and amount of diffused light by arranging interferential controls on the machines, but nothing can be done to remove, or even lessen, aberrations which gravely detract from image quality, except by the use of costly, cumbersome, and always imperfect correction mechanisms. Holographic gratings were developed on an entirely different ruling principle to circumvent these defects (Figure 1).

A Grating Made in Twenty Minutes

Holography is a procedure permitting the phase and amplitude of a wave to be recorded on a photosensitive support by making it interfere with another wave, called reference wave. The phase is characterized by the distribution and shape of the interference fringes, and the amplitude by the contrast between dark and bright fringes. Of course, for interference to take place, the two waves must be coherent, which requires the use of lasers with great coherence length.

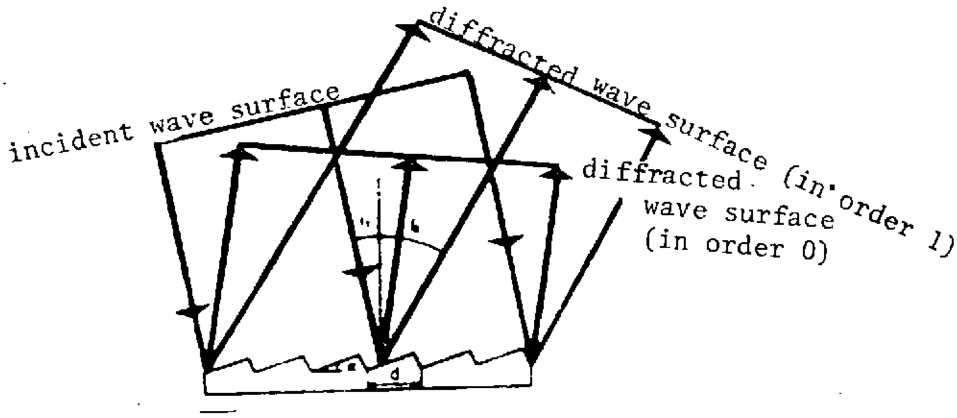


Figure 1. Diffraction diagram for a classical plane grating: the incident wave surface (wave length λ) is diffracted in several orders. (The directions of diffraction are such that $i_2 = \sin i_1 + k \lambda/d$). The energy distribution in the various orders depends on the "blaze α" angle and on the polarization state of the incident wave. For diffracted wave surfaces to be plane the periodicity of the grating's rulings must be rigidly adhered to, its substrate must be plane, and the incident wave surface must be plane. Experimentally, the shapes of wave surfaces have been observed with a Michelson interferometer: the diffracted wave is here compared to a plane reference wave. The interference fringes observed characterize the shape of the wave surface, just as the contour lines on a map represent the relief.

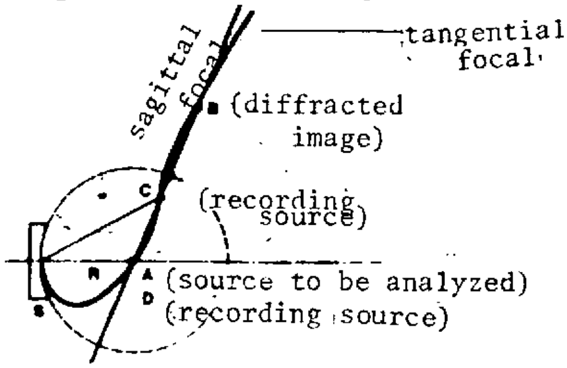
The sensitive plate when developed may be re-lighted by the reference wave. We then have amplitude and phase reconstruction of the original wave, and thus of the object that caused it. This reconstruction process generally gives fairly dark images marred by aberrations if the restoring wave has a different direction and wave length to the reference wave.

In the manufacturing process invested by the Jobin-Yvon company /76 team (G. Pieuchard, A. Lebeyrie, J. Flamand and J. Cordelle) who, with the aid of CNES and DRME, developed this type of grating, a support made of glass or any other optically polished material is coated with a layer of photopolymerizable resin which records the interference phenomenon produced by two coherent point sources defined by a laser. The resin polymerizes along the bright fringes and can then be dissolved in a suitable developer. After rinsing and drying, a diffraction grating is obtained, and this can then be metallized. Twenty minutes suffice to produce a grating on a substrate 150 x 150 mm in area, with, for example, 1200 rulings per millimeter. The shape of the substrate and the position of the source points depend mainly on conditions set by the user; the average "pitch" is a function of the geometry of the rays and the position of the sensitive surface. Of course, the manufacturing process itself is proof against any periodic or random error in placing the grooves, which removes ghosts and diffused light.

Moreover, the complete study of aberrations in these new optical systems shows that there exist pairs of points: light source to be analyzed and images diffracted by this source, with no aberration whatever for wave lengths determined by simple geometric considerations (equation of the sensitive surface, position of recording sources, position of source to be analyzed (Figures 2 and 3).

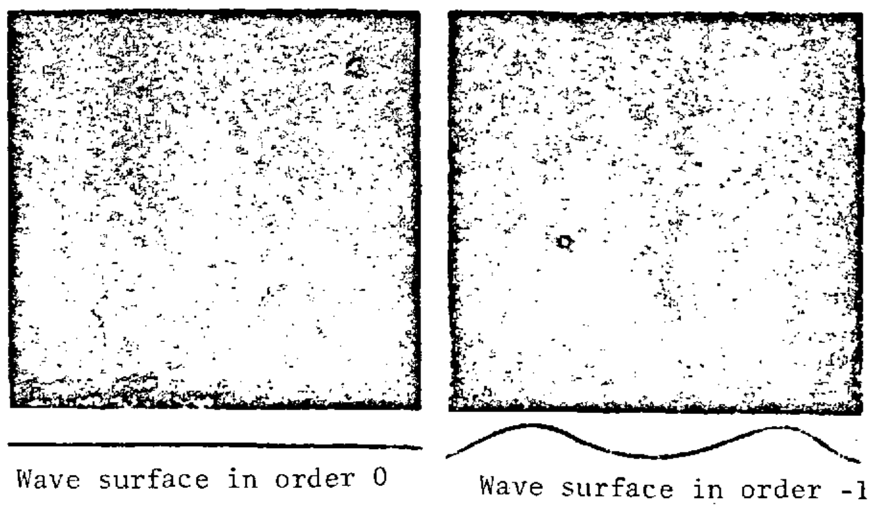
We have to be concerned not only with the quality but with the brightness of the images. The phenomenon of diffraction by a grating is a consequence of Helmholtz's equation, which governs the propagation of electromagnetic waves and the structure of the groove profile. To calculate the diffracted intensity, we must write Maxwell's equations (from which Helmholtz's equation was derived) plus boundary conditions, and take into account the vectorial nature of the electromagnetic field. In fact, the value of the diffracted energy is quite different according to the polarization state of the incident field. One generally considers the following two cases: the electric field is parallel to the grooves (configuration E); and the magnetic field is parallel to the grooves (configuration H).

Figure 2. Thanks to holographic gratings, concave gratings may be constructed with a given average "pitch", absolutely anastigmatic for three given wave lengths.



(The images for other wave lengths are slightly marred by aberrations, but these are small compared with those of classical concave gratings.) S is the sensitive surface supporting the grating. C and D are the positions of the two sources of wave length λ which served to manufacture the grating. A is the polychromatic source we wish to study. In the configuration opposite, the images focused at A, C, and B (corresponding to three different wave lengths) have no aberrations whatever. The grooves of the holographic gratings are the lines of intersection of equiphase surfaces in phase with the sensitive surface.

Figure 3. Interferograms of diffracted wave surfaces in order 0 (left) and -1 (right) by a "Schmidt blade" holographic grating. Their purpose is to correct the spherical aberration of a Cassegrain telescope, by providing spectral analysis of the sources studied (Plates from Jobin-Yvon).



1) These equiphases are generally evolution quadrics of the focus C and D, but far more complex surfaces may be made of them by introducing, for example, supplementary phase information into one of the beams (see Figure 3).

The efficiency of the gratings, i.e. the ratio between diffracted flux and incident flux for a given radiation, is well known for plane metal gratings with a triangular profile. Theoretical studies, remarkably well borne out by experiment, permit their energy properties to be predicted. But the profile of holographic gratings is far from being triangular, and many efficiency problems remain to be solved. Experimental studies have been conducted on wave lengths in the visible range. These show that the maximum efficiencies obtained are very much comparable with those derived with classical, densely-ruled gratings. In fact, if the efficiency depends on the profile, it also depends on many other factors: thickness of the resin layers, length of exposure and development, nature of metal or dielectric deposit after chemical treatment. A systematic study has been undertaken, with the collaboration of the theoreticians (in particular Mr. Petit, chief lecturer at the Marseilles Faculty of Sciences). This collaboration has proved fruitful in studying the energy properties of classical plane metal gratings (Figures 4 and 5).

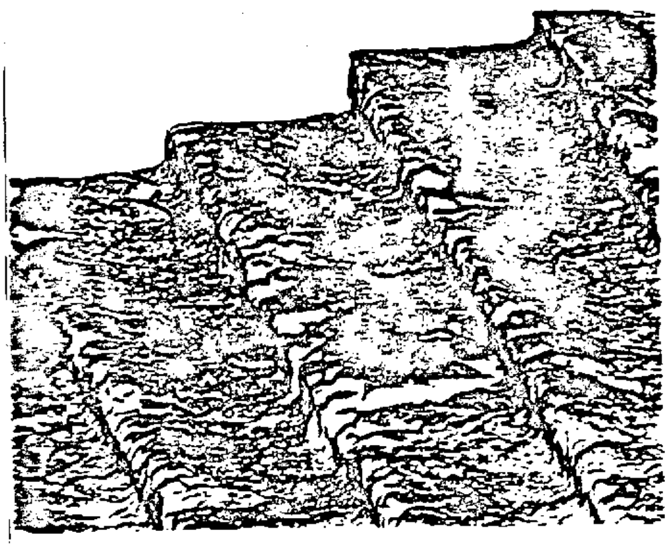
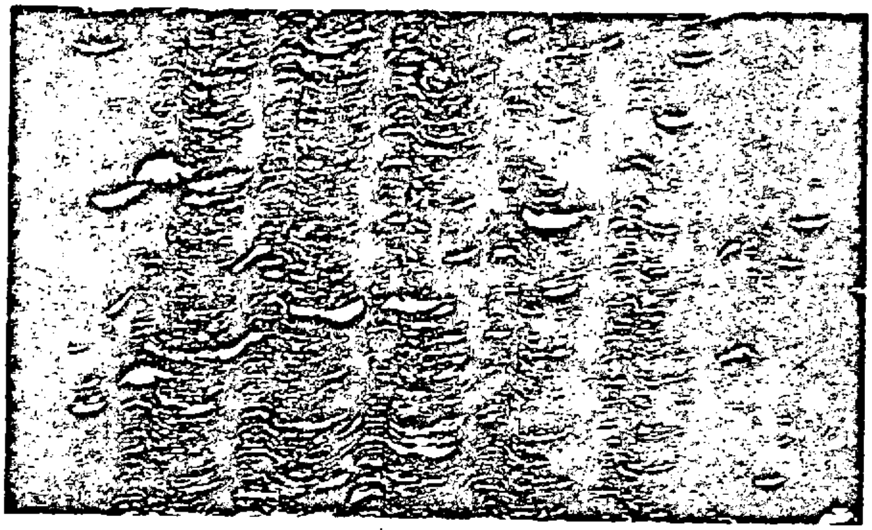


Figure 4. Micrograph of a classic grating (left) and of a plane holographic grating (right) with 1200 rulings per millimeter.

Plates from the Crystal Optics and Physics Laboratory, Faculty of Sciences, Marseilles).

Figure 4. (right)



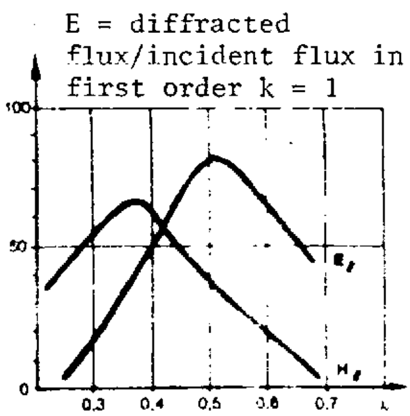


Figure 5. Efficacy curve of a holographic grating with 2000 rulings per millimeter. Under well-defined experimental conditions, the ratio of the incident flux to the diffracted flux is measured as a function of the wave length and the polarization state. These curves show the manner in which the light energy is distributed throughout the spectrum.

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